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HEAT BALANCE OF AGRICULTURAL SOILS

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ABSTRACT. Various heat balance factors of agricultural soil, such as thermal characteristics, thermal distribution at the surface, and reaction of plants to temperatures are described and the effect agricultural and cultivation-technical measures has on soil temperature is discussed.

1. Introduction /146*

In examining the heat balance of agricultural soil, we distinguish between the following aspects:

1. thermal characteristics of the soil, in this case specific heat and heat conductivity;
2. thermal distribution at the surface of the earth between ground and air, and the effect of agricultural and cultivation-technical measures on this distribution;
3. the reaction of the plant to the temperature of the surface soil and of the adjacent air layer.

The heat balance of this microclimate zone, apart from a great variety of empirical research, has also been the subject matter of theoretical research, for instance by Peerlkamp (1944), de Vries (1952), Lettau (1951), and van Duin (1956).

As far as the reaction of the plant to temperatures in the cultivation area is concerned, many research results are available; however, our understanding of the process is only fragmentary. It is, for instance, not entirely clear to what extent the course of temperature, rather than aeration, constitutes the limiting factor in the case of wet "cold" ground. This aspect will be dealt with in a very summary fashion.

2. The Effect of Temperature on Plant Growth

With respect to the effect of the temperature upon plant growth, the use

* Numbers in the margin indicate pagination in the foreign text.

of heat quantities is interesting, since such a procedure makes it possible to compute the effect of certain measures on growth. (The possible physiological background is not taken into consideration in this context).

An example of the use of heat quantities is supplied by the research of Kramer (1955), which deals with the germination of barley. In this connection, it becomes apparent that the germination processes are not of significance until the average temperature during a 24-hour period exceeds 1.5°C. The seed subsequently germinates fully, provided the sum of the average 24-hour temperatures, above this so-called threshold value, amounts to a total of 100.

By raising soil temperature through specific measures, it becomes possible to compute how much sooner this heat total of 100 "degree days" is attained, and also how much sooner the seed germinates.

Apart from this threshold temperature for germination, the freezing point /147 also represents a significant critical value with respect to the occurrence of certain calamities, such as frost damage during severe winters as well as night frost. In view of the fact that the temperature of the cultivation area can be influenced by agricultural measures only within very narrow limits, heat balance of the soil is, in general, of minor agricultural importance, in the case of a greenhouse adapted to the climate. As far as horticulture is concerned, where it is very important for the products to get to market at the earliest date possible, the care of plants is affected not only by the occurrence of frost damage, but also by the acceleration of the harvest.

3. Heat Flow in the Soil and its Distribution in Depth

The following factors play a part with respect to the course of temperature in the soil and in the adjacent air layer:

1. Heat prevailing at the soil-air boundary surface:

$$U = R_i - R_r - V. \tag{1}$$

Where irradiation, R_i and radiation R_r, are more or less fixed values, so that the available heat, U depends primarily on evaporation, V.

2. Distribution of heat, available at the boundary surface between soil and air:

$$U = B + L \tag{2}$$

where B and L respectively, refer to the heat flowing towards the soil and the heat flowing towards the air. Heat currents flowing towards the soil and towards the air are partially dependent upon the thermal qualities of these media, based on the equation:

$$B_O = A_O\sqrt{\lambda C\omega} \tag{3}$$

Here, B_O and A_O, respectively, represent amplitudes of the heat flow in the soil and of temperature flow on the surface of the ground, whereas λ and C represent, respectively, heat conductivity and specific heat of the soil; ω expresses the period of periodical function under consideration. A similar equation applies to heat flow in the air.

3. The distribution of heat, available for the soil, in relation to the depth which depends upon the thermal characteristics of the soil, in accordance with the equation (based on homogeneous soil):

$$A_z = A_O e^{-z/D}.$$

A_O and A_z indicate the amplitude of the temperature flow at depths 0 and z, respectively. Attenuation depth, D, follows from the equation:

$$D = \sqrt{2\lambda/C\omega} \tag{4}$$ /148

This attenuation depth constitutes a measuring standard for the depth to which the heat flow penetrates. At depths equaling one, two, three, and four times D, the amplitude amounts to 37, 14, 5, and 2% of the surface amplitude, respectively.

4. Thermal Characteristics of the Soil

The above findings show that thermal characteristics of the soil determine to a large extent the distribution of the available heat between soil and air. As far as specific heat of mineral soil is concerned, the following equation applies:

$$C = 0.46\ X_v + X_w,$$

whereby X_v and X_w indicate the volume fractions of solid particles and water. The heat conductivity also increases, as the volume fractions of solid particles and water increase in size. This is shown in Table 1, which lists apart from thermal characteristics of the various soil components, the thermal characteristics of sand, clay, and peat at varying stages of density and moisture content.

TABLE 1. THERMAL CHARACTERISTICS OF VARIOUS SOILS AT VARYING STAGES OF DENSITY AND MOISTURE CONTENT

	Volume fraction						Attenuation depth	
	Solid	Water	Air	Heat conductivity (λ) x 10^3	Specific heat (C)	$\frac{1}{\sqrt{\lambda C}}$	Yearly	Daily
SOIL COMPONENTS	I	II	III	IV	V	VI	VII	VIII
1 Quartz	1.0	-	-	20.0	0.46	10	660	35
2 Other minerals	1.0	-	-	7.0	0.46	18	390	20
3 Organic matter	1.0	-	-	0.60	0.60	53	100	5.2
4 Water	-	1.0	-	1.4	1.0	27*	120	6.2
5 Saturated air	-	-	1.0	0.24	$0.30.10^{-3}$	1200*	90	4.7
6 Dry air	-	-	1.0	0.062	$0.40.10^{-3}$	7.10^{5}*	450	24
COMPACT SOIL								
7 Sand (Eng.): dry	0.60	-	0.40	0.63	0.28	76	150	7.9
8 tillage capacity	0.60	0.19	0.21	3.8	0.47	24	285	15
9 saturated	0.60	0.40	-	4.8	0.68	18	265	14
10 Clay (Nude): dry	0.60	-	0.40	0.60	0.28	78	140	7.6
11 tillage capacity	0.60	0.24	0.16	3.36	0.52	24	250	13
12 saturated	0.60	0.40	-	3.9	0.68	20	240	12
13 Peat (crust): dry	0.15	-	0.85	0.092	0.091	350	100	5.3
14 tillage capacity	0.15	0.75	0.10	1.12	0.84	33	120	6.1
15 saturated	0.15	0.85	-	1.28	0.94	29	120	6.1
LOOSE SOIL								
16 Sand (Eng.): dry	0.40	-	0.60	0.33	0.18	129	140	7.1
17 tillage capacity	0.40	0.125	0.475	1.7	0.31	44	230	12
18 saturated	0.40	0.60	-	3.3	0.78	20	210	11
19 Clay (Nude): dry	0.40	-	0.60	0.34	0.18	127	140	7.2
20 tillage capcity	0.40	0.16	0.44	1.8	0.34	40	230	12
21 saturated	0.40	0.60	-	2.9	0.78	21	190	10
22 Peat (crust): dry	0.10	-	0.90	0.061	0.061	450	115	6.0

		Volume fraction							
		Solid	Water	Air	Heat conductivity (λ) x 10^3	Specific heat (C)	$\frac{1}{\sqrt{\lambda C}}$	Attenuation depth Yearly	Attenuation depth Daily
23	tillage capacity	0.10	0.50	0.40	0.68	0.56	51	110	5.8
24	saturated	0.10	0.90	-	1.32	0.96	28	120	6.1
SAND									
25	Grain texture	0.40	0.125	0.475	1.7	0.31	44	230	12
26	Crumb texture	0.40	0.125	0.475	0.98	0.31	58	180	9.3

* Exclusive of heat conveyance through displacement of water or air; λ is expressed in cal/cm - sec - °C; C in cal/cm^3 - °C; D in cm.

5. Effect of Soil Thermal Characteristics on Surface Temperature /149

Heat exchange at lower levels is reduced in proportion to soil heat conductivity. The result is to cause the surface temperature to rise more rapidly during warming periods and to drop more rapidly during cooling periods. This effect is greater, the lower the specific heat of the soil, because less heat is required to raise the temperature. Thus, the difference between the maximum and minimum surface temperatures increases in proportion to the decrease in heat conductivity and specific heat. This is evident from Eq. 3, which can be written:

$$A_0 = B_0\sqrt{\lambda C \omega}\,.$$

The values of $1/\sqrt{\lambda C}$ are listed in column VI of Table 1 for different components and soil types. From this, it is evident that temperature fluctuations are greater, the looser and drier the soil, and the more organic substances it contains. A comparison of these values for various soil types and moisture contents also indicates possible differences in the occurrence of high and low temperatures. This follows mathematically from Eq. 3, since in two situations involving thermal magnitudes $\lambda_1 C_1$ and $\lambda_2 C_2$, amplitudes, if B_0 heat flow is the same, act as follows:

$$A_1/A_2 = \sqrt{\lambda_2 C_2} \cdot \sqrt{\lambda_1 C_1} \qquad (5)$$

The amplitude of surface temperature for loose soil of tillage capacity is 44/24 = 1.8 times as great as for compact soil at tillage capacity, with the heat flow being identical in both cases (items 17 and 8 of Table 1).

In reality, however, this amplitude is not quite proportional to $1/\sqrt{\lambda C}$, because the distribution of the available heat between soil and air depends on the thermal characteristics of the soil. This implies that B, too, varies with λ and C, and that the conversion of Eq. 3 into Eq. 5 is not necessarily acceptable.

TABLE 2. AMPLITUDE RATIO OF DAILY TEMPERATURES AT THE SURFACE (WITH RESPECT TO MODERATELY COMPACT SAND AT TILLAGE CAPACITY: $X_v = 0.50$; $X_w = 0.16$; $1/\sqrt{\lambda C} = 31$).

$1/\sqrt{\lambda C}$	at identical heat flow	at adapted heat flow
Sand, saturated: 19	0.61	0.73
Closely pressed sand, tillage capacity: 24	0.77	0.86
Losse sand, tillage capacity: 44	1.42	1.20
Loose peat crust, tillage capacity: 51	1.66	1.30
Sand, dry: 95	3.09	1.57
Peat crust, dry: 450	14.6	1.97

This is shown for a number of cases in Table 2, which summarizes the amplitude ratios computed in accordance with Eq. 5, as well as amplitude ratios that may actually be anticipated. The first figure column in the table refers to the amplitude ratio for identical heat flow, the second column to the amplitude ratio for adapted heat flow. /150

Figure 1, 2, and 3 show the computed daily temperature for a number of cases. Figure 1 shows the differences in type of soil and depth; Figures 2 and 3 the differences in compactness and moisture content.

According to Figure 1, the night frost zone of peat crust for this temperature lies between a depth of 1.5 centimeters and a height of 6 centimeters, since the amplitude in that zone is greater than the average 24-hour temperature, so that the minimum temperature lies below 0°. According to Figure 3, the decrease in moisture content from a state of saturation to a tillage-capacity state does

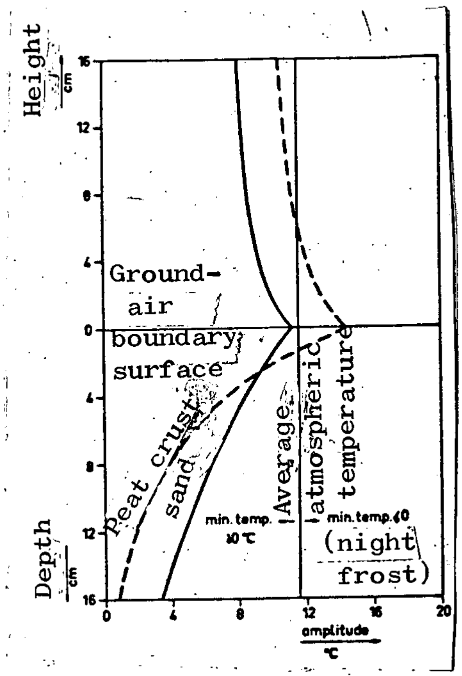

Figure 1. Examples of the decrease in amplitude of daily temperatures, as result of increasing distance from the air/ground boundary surface.

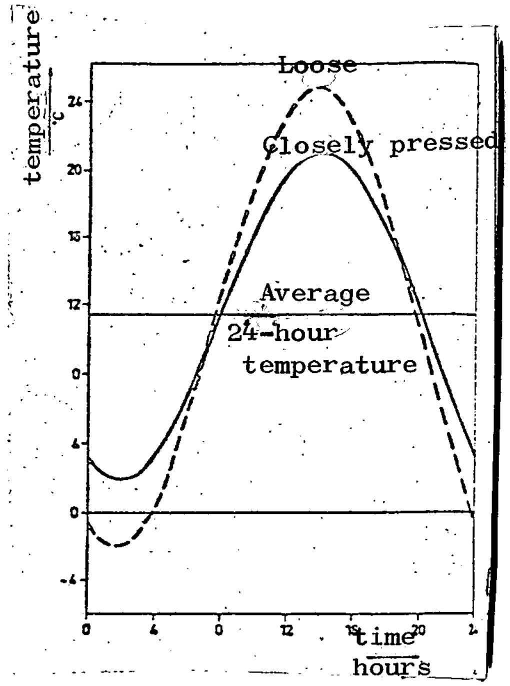

Figure 2. Daily temperature fluctuations on the surface of sandy soil at varying degrees of soil compactness.

not so much lead to an increased danger of night frost, although the greatest degree of moisture is involved, as to a desiccation below tillage capacity. In computing the course of the temperature it has been assumed that the quantity of heat available at the boundary surface is identical whether the soil is wet or dry. However, if evaporation during the dry stage is zero, the amplitude does not increase from 11.2 to 17.5°C, but to 26.5°C, whereby the average 24-hour temperature is also going to be higher.

6. Effect of Agricultural and Cultivation-Technological Measures On Temperature /151

The foreseeable effect of certain agricultural and technological measures depends primarily upon the thickness of the soil layer involved in heat exchange. If this soil layer is several meters thick, the loosening of the top layer, for instance, is going to have decidedly little effect on the behavior of soil temperature. The depth of the heat flow ensues, as per Eq. 4, from attenuation depth $D = \sqrt{2\ \lambda/C\omega}$, where $\omega = 2\ \pi/\tau$, if τ represents the circulation period of the heat flows and temperature fluctuations under consideration. The equation applying to attenuation depth can thus be formulated as follows: $D = \sqrt{\lambda\tau/C\pi}$.

The depth, to which the heat flow penetrates, depends largely on the circulation time τ; it is obvious, for instance, that the annual flow penetrates considerably deeper into the ground than the daily flow. This depth increases, the better the soil transmits heat, and the smaller the quantity of heat that is being tied up. Table 1 summarizes the values for the annual and daily flow stream for a number of examples. If the soil is wet and compact, the heat flow penetrates to a considerably greater depth than in dry, loose soil; it penetrates deeper in mineral soil, than in peat soil.

In summary, it may be said that the effect of certain measures upon the temperature behavior increases, the smaller D is, and the greater the difference between $1/\sqrt{\lambda C}$ in the original condition and $1/\sqrt{\lambda C}$ in the changed condition. /152

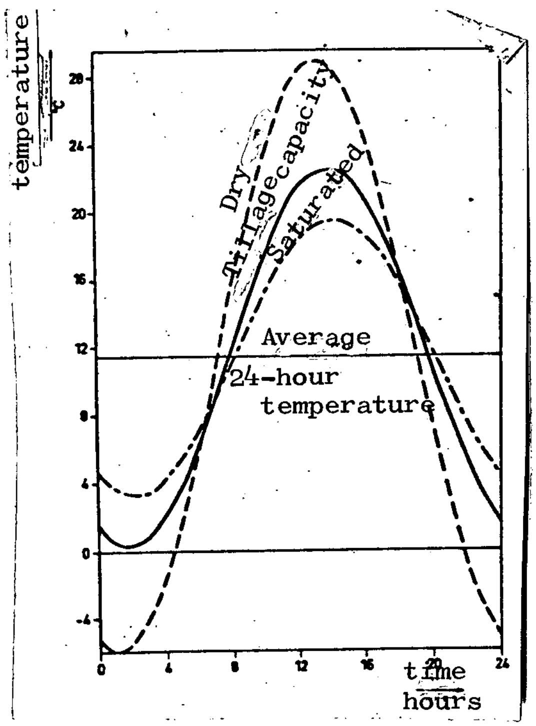

Figure 3. Daily temperature fluctuations on the surface of sandy soil at varying degrees of moisture content of the soil.

Moreover, the effect of certain measures, which change, the thermal characteristics of the topsoil, for instance, generally lies somewhere between the condition, in which the soil possesses, the characteristics of the bottom layer down to a considerable depth, and the condition, in which the soil posseses topsoil characteristics down to a considerable depth. For example, the effect of loosening the topsoil is, at most, equal to the effect resulting from the temperature behavior, shown in Figure 2, in soil that is loose down to a considerable depth. It may, therefore, be appropriate to ask to what depth topsoil must be changed, in order to closely approximate this extreme condition. Some examples, outlined in Figure 4, show that bottom layer characteristics generally no longer affect the fluctuations of the surface temperature, whenever the thickness of the topsoil layer is approximately equal to the attenuation depth.

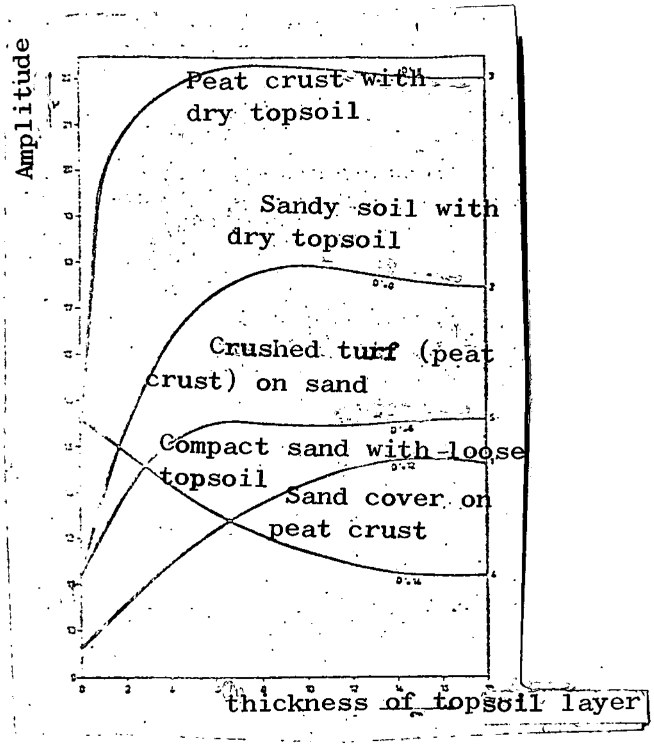

Figure 4. Effect of topsoil layer thickness on amplitude of daily temperature fluctuations on the surface.

(a) Tillage of the Soil /153

Curve 1 in Figure 4 indicates the effect loosening of the topsoil has on the daily temperature amplitude on the surface, which increases from 9.6°, when thickness of the top layer d = 0, to 13.7°, when d = 15 centimeters. If d = D = 12 centimeters, the amplitude has already risen to 13.5°C or 95% of the maximum increase. The effect of the soil tillage on annual temperature fluctuations is considerably lower and amounts to no more than a few tenths of 1°C. It ought to be noted in this connection that the effect during springtime is, of course, opposite to the fall effect. This leads to a somewhat accelerated temperature rise in spring, whereas it results in a somewhat accelerated cooling-off process in the fall. Opposite effects also apply to the topsoil and bottom layer, since the more rapid temperature rise in the loose top soil coincides with a slower temperature rise in the bottom layer due to the insulating effect of the layer. In fall, the reverse holds true. These facts may be of some significance for germination and for the possibility of frost damage, whereby such influence is enhanced by the occurrence of fluctuations of shorter duration. To the extent, however, that this leads to accelerated germination, the effect is frequently nullified again in the course of the subsequent period.

(b) Topsoil Desiccation

Curve 2 in Figure 4 shows the amplitude increase through desiccation of the top layer of sandy soil. When d = D = 8 cm, the amplitude has already increased from 11.2 to 17.8°C, corresponding to 98% of the maximum increase. The same applies to peat crust with a dry top layer (curve 3). If, in this connection, the decline in evaporation is also taken into consideration, then the amplitude for sand does not increase from 11.2 to 17.9°C, but to 33.4°C (except for an insignificant rise in radiation).

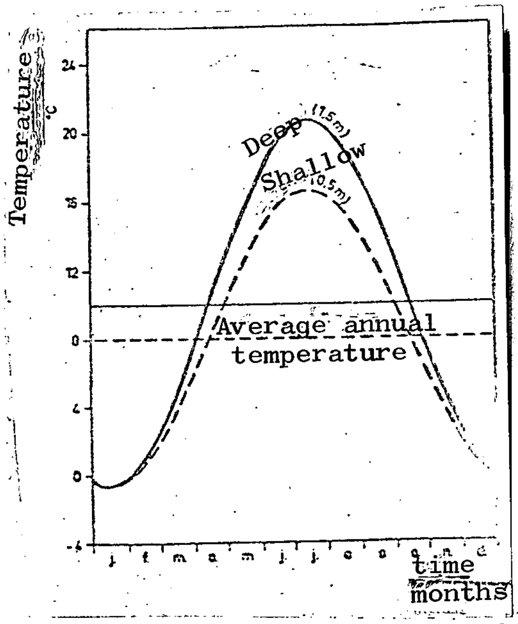

Figure 5. Computed annual course of the average 24-hour temperature on the surface of sandy soil, at various ground water depths.

(c) <u>Sand Cover on Top of Peat</u> /154

The decrease in danger of night frost by means of a sand cover on top of peat is clearly evident from curve 4 (Figure 4). The amplitude of daily temperature of the peat crust is diminished, through a sand cover of d = D = 14 cm, from 14.6 to 11.2°C. At an average 24-hour temperature of, 120°C for instance, (a reasonable value during a period of night frost), the danger of night frost is thus considerably reduced. If the sand cover is 12 centimeters thick, which is the customary thickness, the effect attained in this example already amounts to about 90% of the attainable maximum result.

For a dry top layer, the amplitude, and thus, the possiblity of night frost, increases considerably, as is apparent from curves 2 and 3; the existence of a sand cover, however, results in a considerably more favorable situation than when such a cover is absent.

(d) <u>Crushed Turf Covering</u>

If the ground is covered with crushed turf, the amplitude of the temperature on the surface of the covering layer is greater than that of a now-covered soil surface (curve 5 in Figure 4), whereas the temperature, which prevails in the soil underneath such a layer, is greatly reduced. This effect is slightly enhanced through the annual temperature variation, as well as through coverage during the winter, but not during the summer, by which means the cooling-off is controlled, but not the heating-up.

(e) <u>Drainage</u>

Figure 5 shows computed fluctuations of the annual temperature in a deep (1.50 meters) and in a shallow (0.50 meters), drained, sandy soil, taking into consideration maximum evaporation of 1.5 and 2.5 mm/24 hours. In this context, the effect of differences in thermal characteristics is slight, i.e. only about 0.2°C. As far as the difference in heat fluctuation due to the assumed difference in evaporation is concerned, the effect amounts to 1.8°C. If both the deep and the shallow drained soils have the same average annual temperature, maximum temperatures are 20.6 and 18.6°C, respectively, whereas minimum temperatures amount to -0.6 and 1.4°C, respectively. On the basis of identical minimum temperatures (a situation which seems to be indicated, but about which no certainty exists), the maxima amount to 20.6 and 16.6°C, respectively, in which case barley, for instance, would germinate one week earlier.

7. Conclusion

As far as the differences in thermal characteristics between two types of soil are concerned, the effect depends upon the time of year and upon the depth. Thus, loose soil near the surface, has a higher temperature during a heating-up period and a lower temperature during a cooling-off period than densely pressed soil. However, the reverse development applies for the bottom layer. Tillage of the ground has an opposite effect on summer and winter plants, as well as on germination and root growth. /155

With respect to discrepancies in thermal characteristics as the cause of different temperature fluctuations, one can speak of warmer or colder only, if both depth and time are taken into consideration.

The effect of specific measures on the average 24-hour temperature is slight, but it can be considerably increased, when temporary deviations from the average annual temperature. However, it is, possible for the course of the daily temperature to be influenced to a considerable degree. The fact that wet soil is "colder" than dry soil must be primarily ascribed to the greater evaporation and the accompanying lower temperature level. Supplementary research in this field seems desirable.

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